Assembling the Milky Way Halo: Clues from Stellar Kinematics and Abundances

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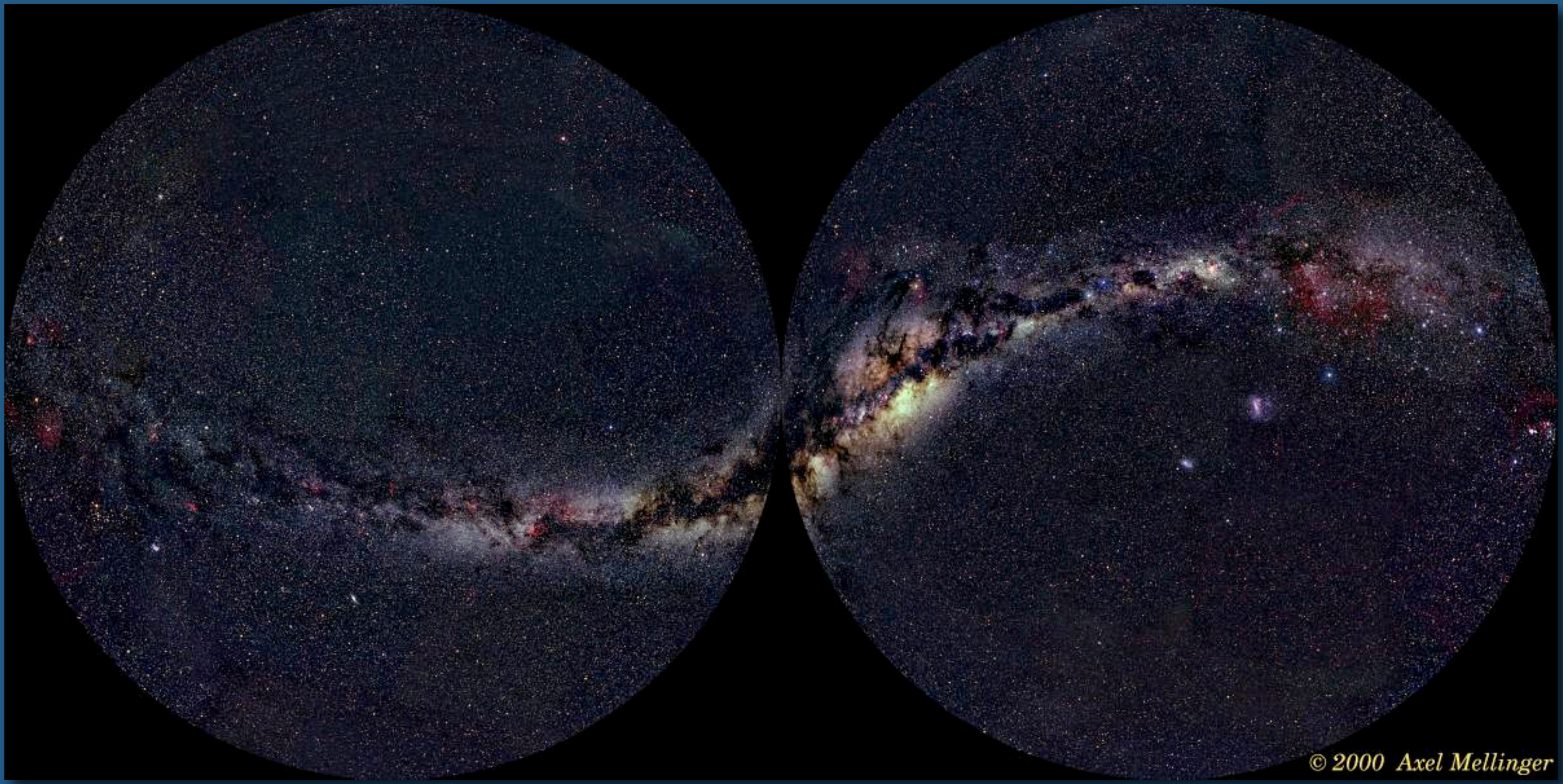
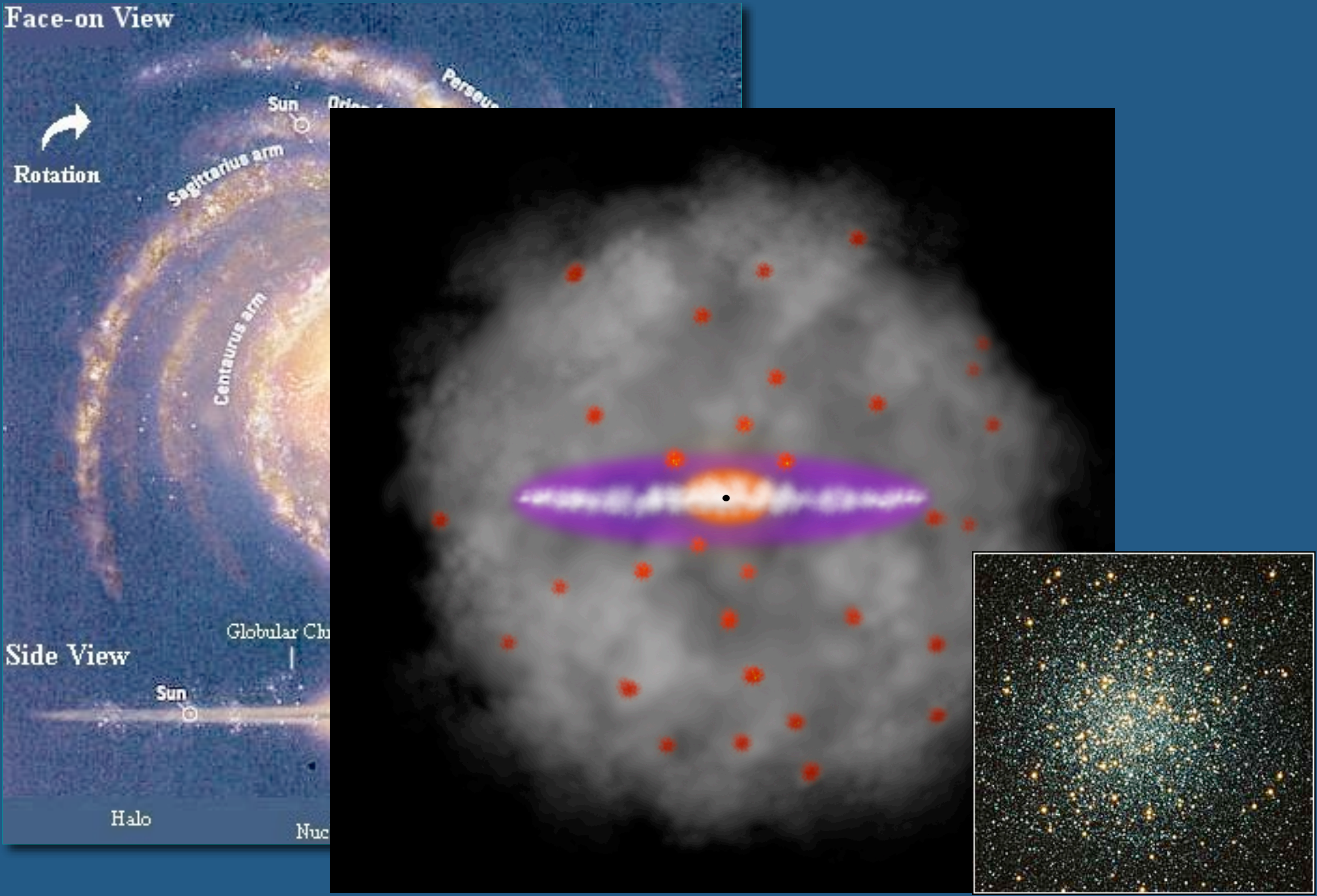
Milky Way's appearance in the Sky



This panoramic view of the entire sky has been assembled from 51 wide-angle photographs. The individual images were transformed to a cartesian frame based on galactic coordinates prior to assembly, thus eliminating the distortions introduced by the wide-angle lens. The final image was then transformed using an equidistant azimuthal (polar) projection.

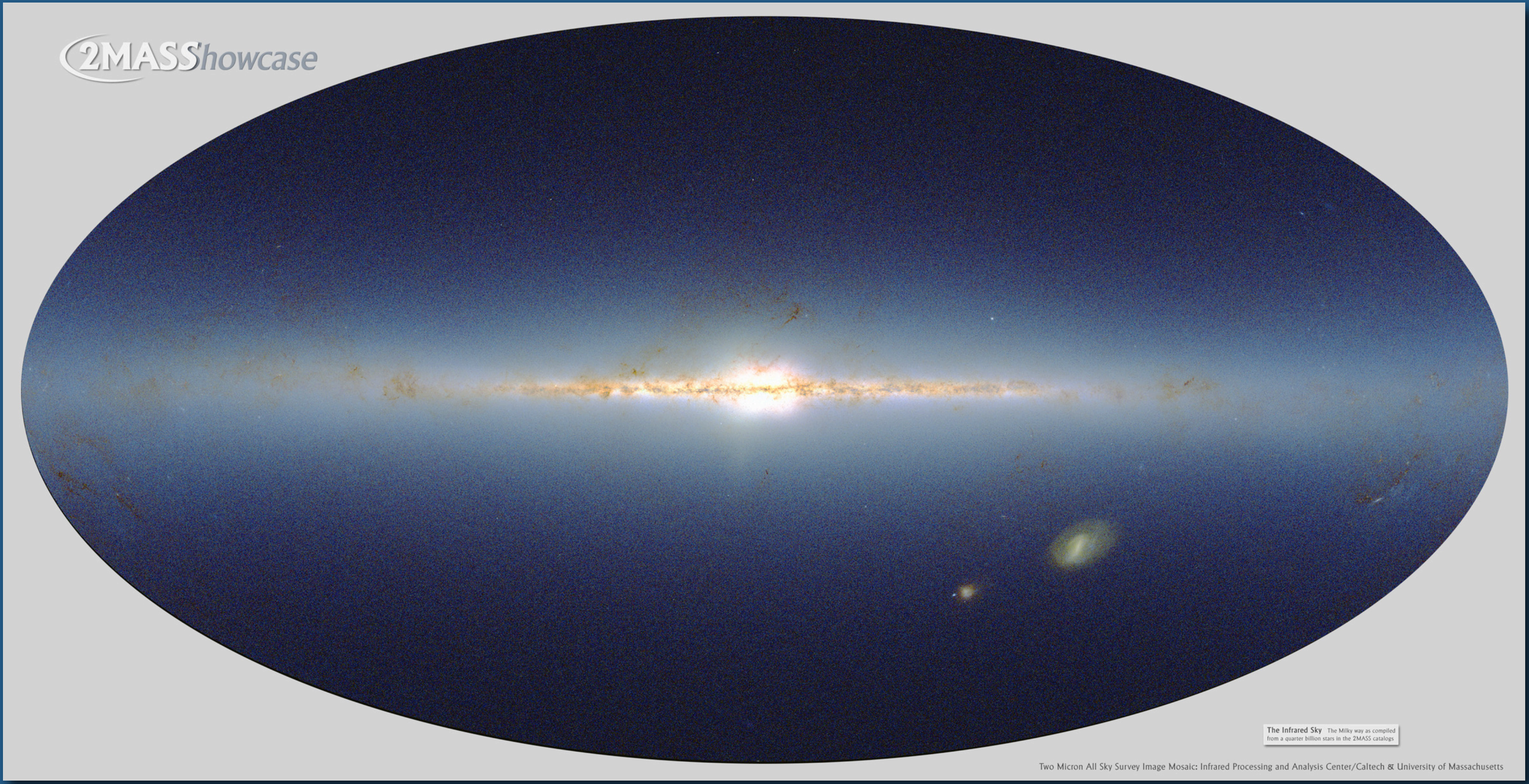
Milky Way’s appearance in a Textbook



All Sky/Large Area Photometric Surveys

2MASS - infrared view of the Milky Way

-compiled from a quarter billion stars in the sky; Cutri et al. 2003

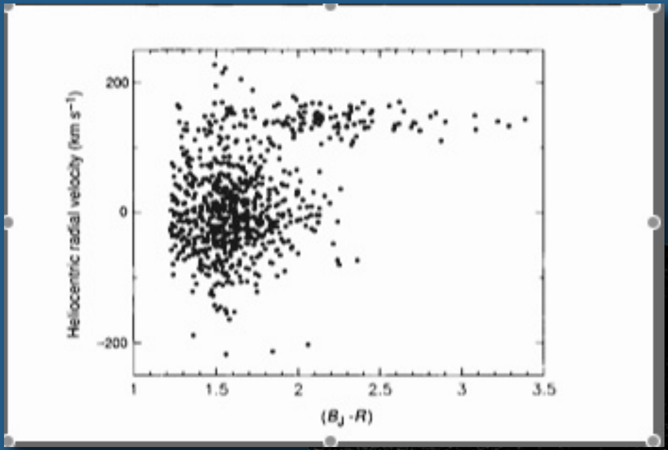


The Infrared Sky The Milky way as compiled from a quarter billion stars in the 2MASS catalogs

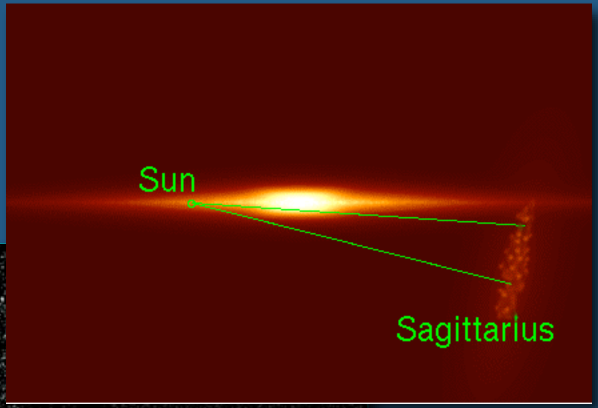
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

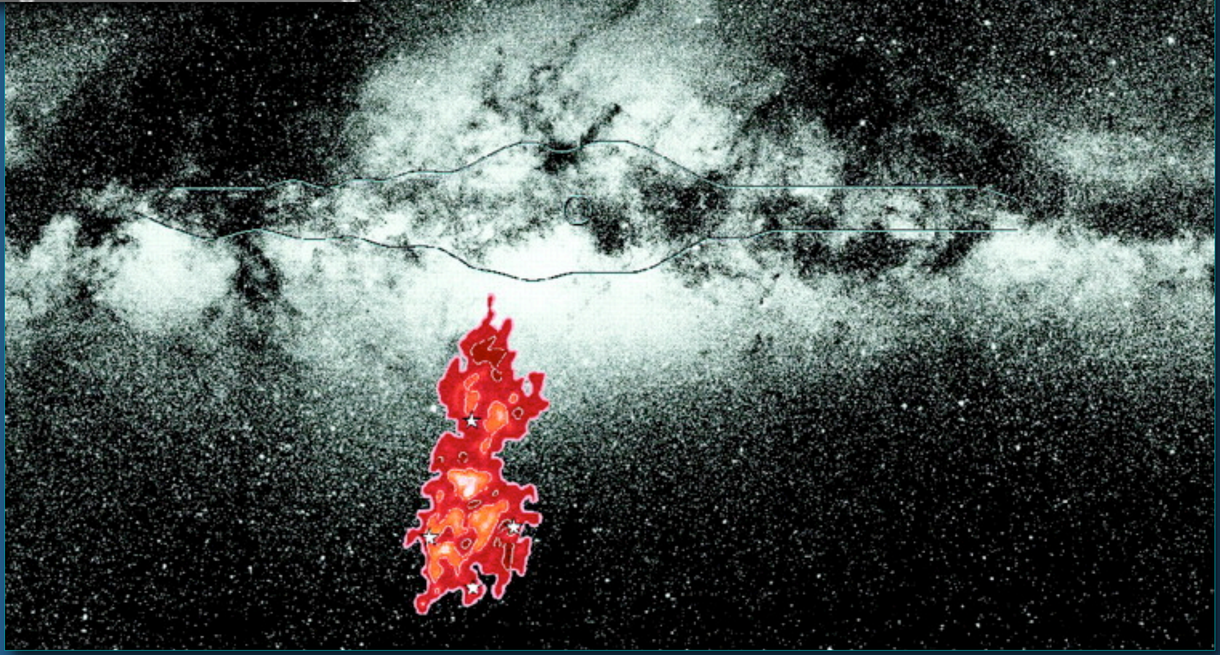
The Sagittarius Dwarf Galaxy

Ibata, Gilmore, Irwin 1994



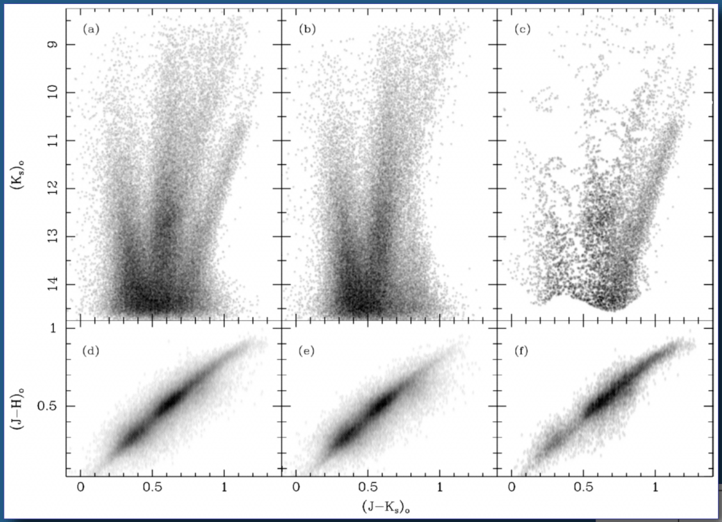
P. Cseresnjes

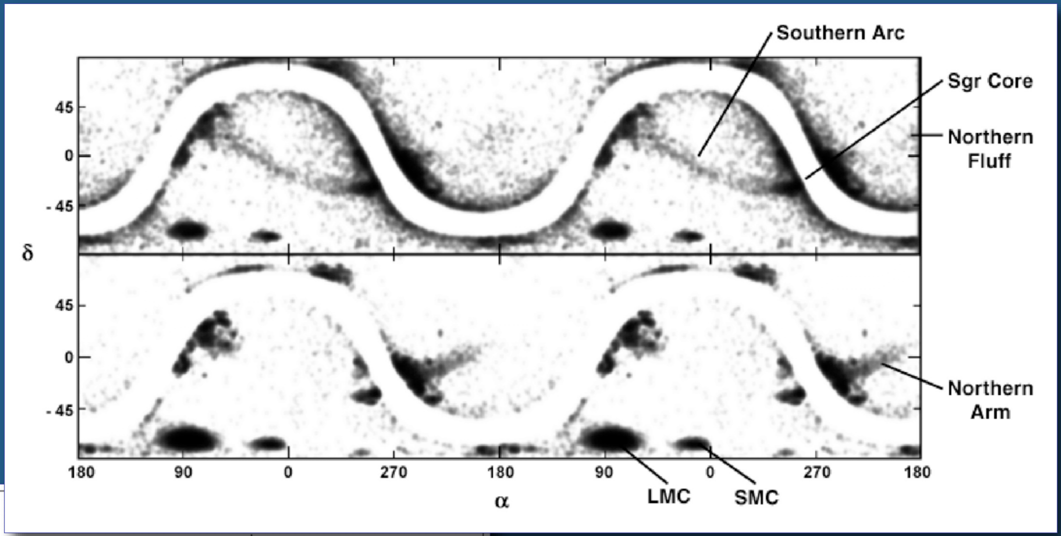


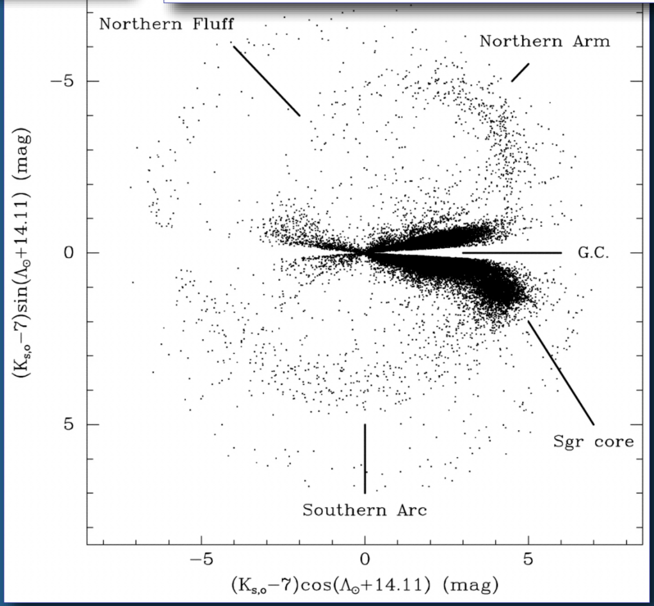


G. Gilmore and R. Sword

The Sagittarius Dwarf Galaxy: Tidal Streams Mapped from 2MASS



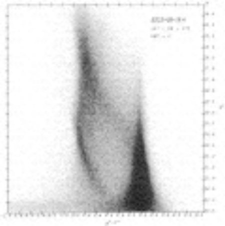




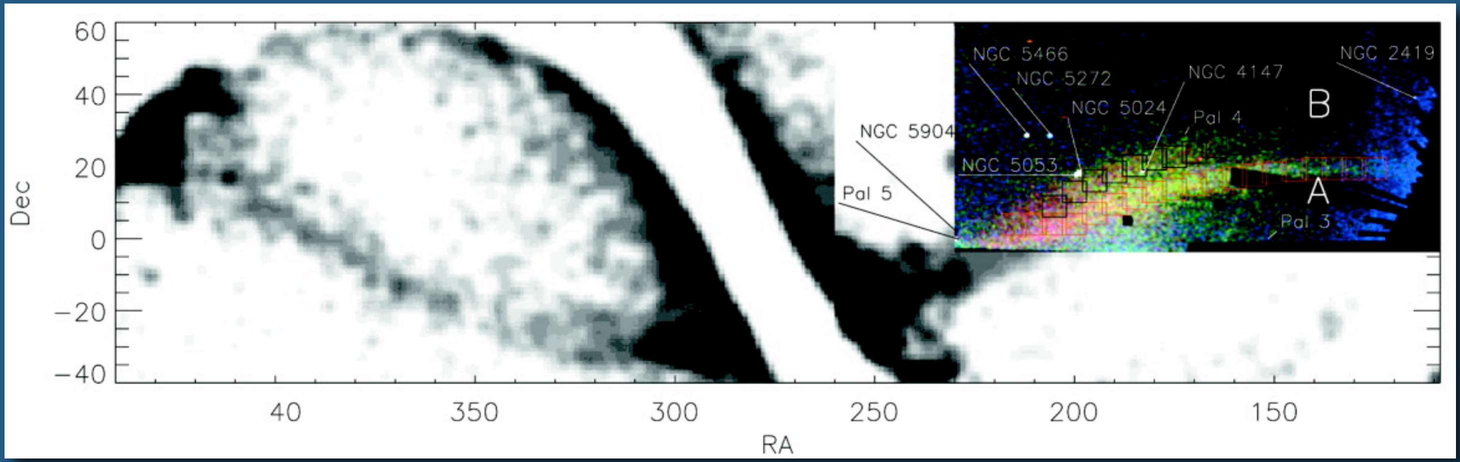
Majewski et al. 2003

Sloan Digital Sky Survey (SDSS)

- to date 8000 sq. deg., 215 million objects
- carried out on a 2.5-m telescope
- initially designed for the study of galaxies and QSOs.

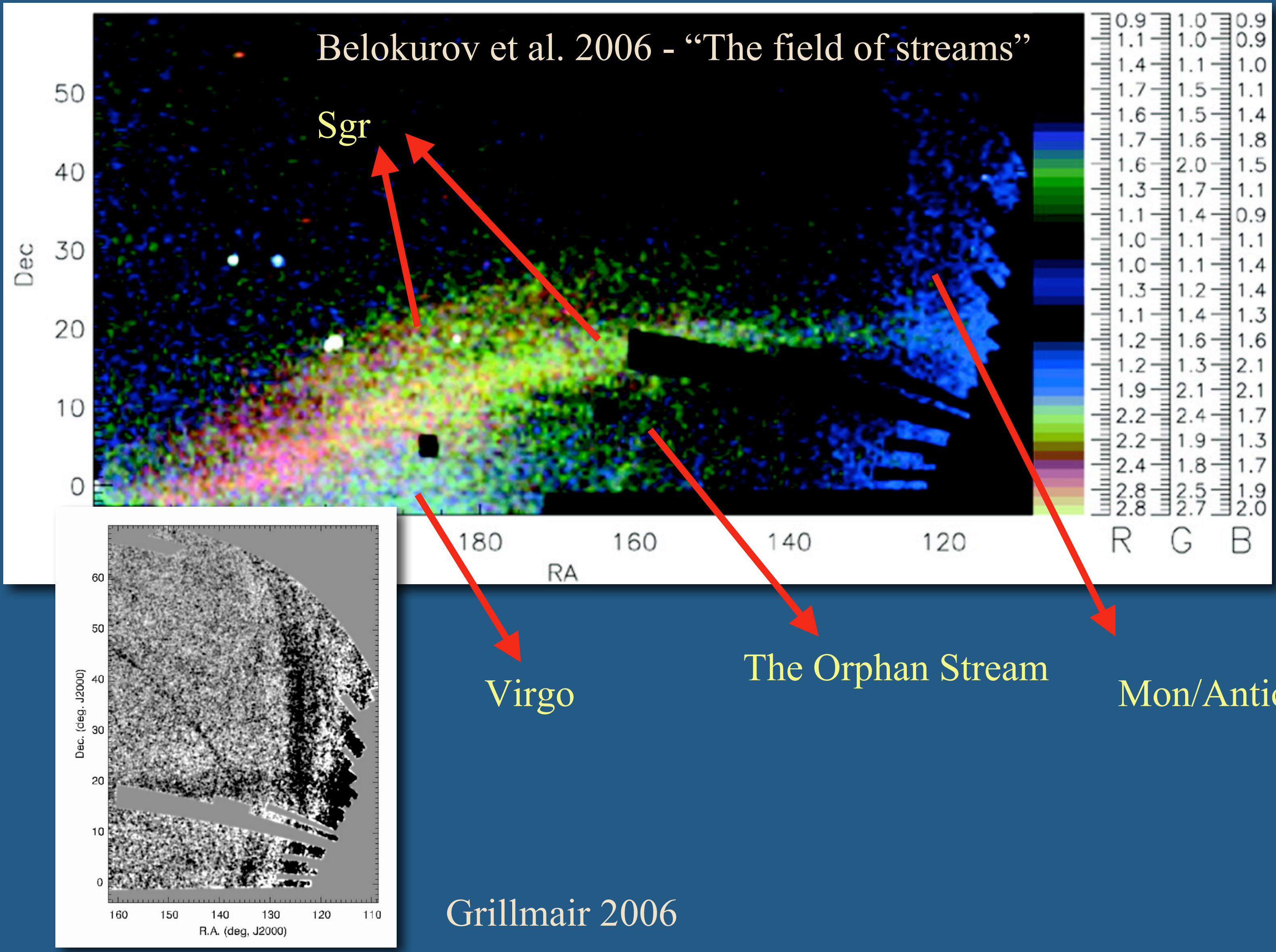


No galaxies! Newberg et al. 2002, Yanny et al. 2003…



SDSS (Belokurov et al. 2006) connecting with 2MASS (Majewski et al. 2003)

SDSS, cont.



Belokurov et al. 2006 - “The field of streams”

Sgr

Virgo

The Orphan Stream

Mon/Anticenter

Grillmair 2006

SDSS, cont.

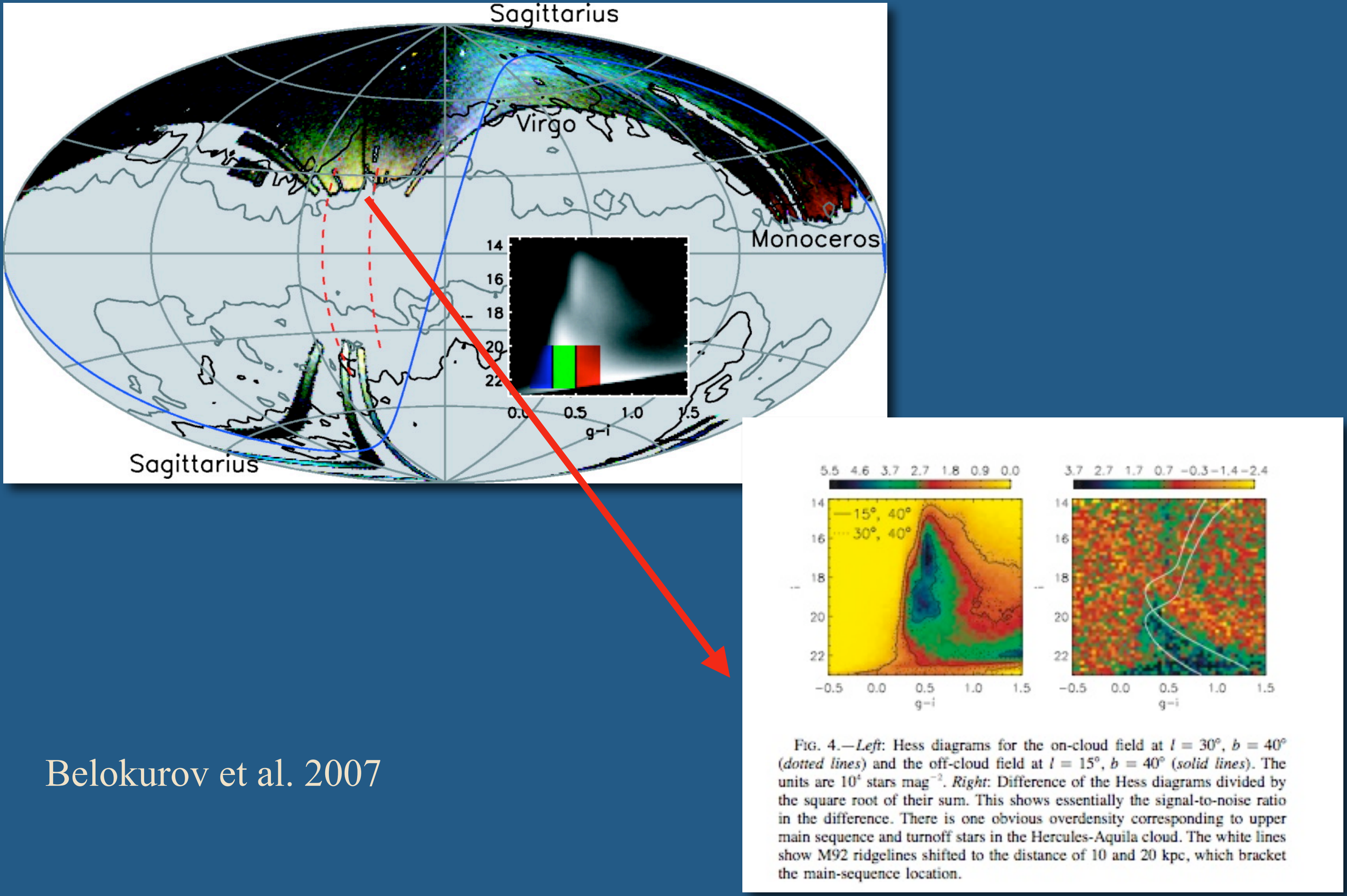


FIG. 4.—*Left*: Hess diagrams for the on-cloud field at $l = 30°$, $b = 40°$ (*dotted lines*) and the off-cloud field at $l = 15°$, $b = 40°$ (*solid lines*). The units are 10^4 stars mag^{-2}. *Right*: Difference of the Hess diagrams divided by the square root of their sum. This shows essentially the signal-to-noise ratio in the difference. There is one obvious overdensity corresponding to upper main sequence and turnoff stars in the Hercules-Aquila cloud. The white lines show M92 ridgelines shifted to the distance of 10 and 20 kpc, which bracket the main-sequence location.

Belokurov et al. 2007

Milky Way’s known halo/thick disk overdensities and tidal streams

Structure	Appearance	Survey	Data
Sgr	Tidal streams, with an almost polar orbit	2MASS, SDSS, RR Lyrae-QUEST, INT, other	Photometry, radial velocities, proper-motions
Mon	Wide tidal streams; possibly related to other overdensities (CMa; Tri-And); circular, in-plane orbit	2MASS, SDSS, INT, RR Lyrae-QUEST	Photometry, radial velocities, proper-motions
Virgo	Diffuse, large area overdensity	SDSS, RR Lyrae-QUEST	Photometry, radial velocities
Hercules-Aquila	Overdensity, large area	SDSS	Photometry, radial velocities
Orphan	Narrow tidal stream	SDSS	Photometry

M 31 and M 33 (Ibata et al. 2007; INT survey)

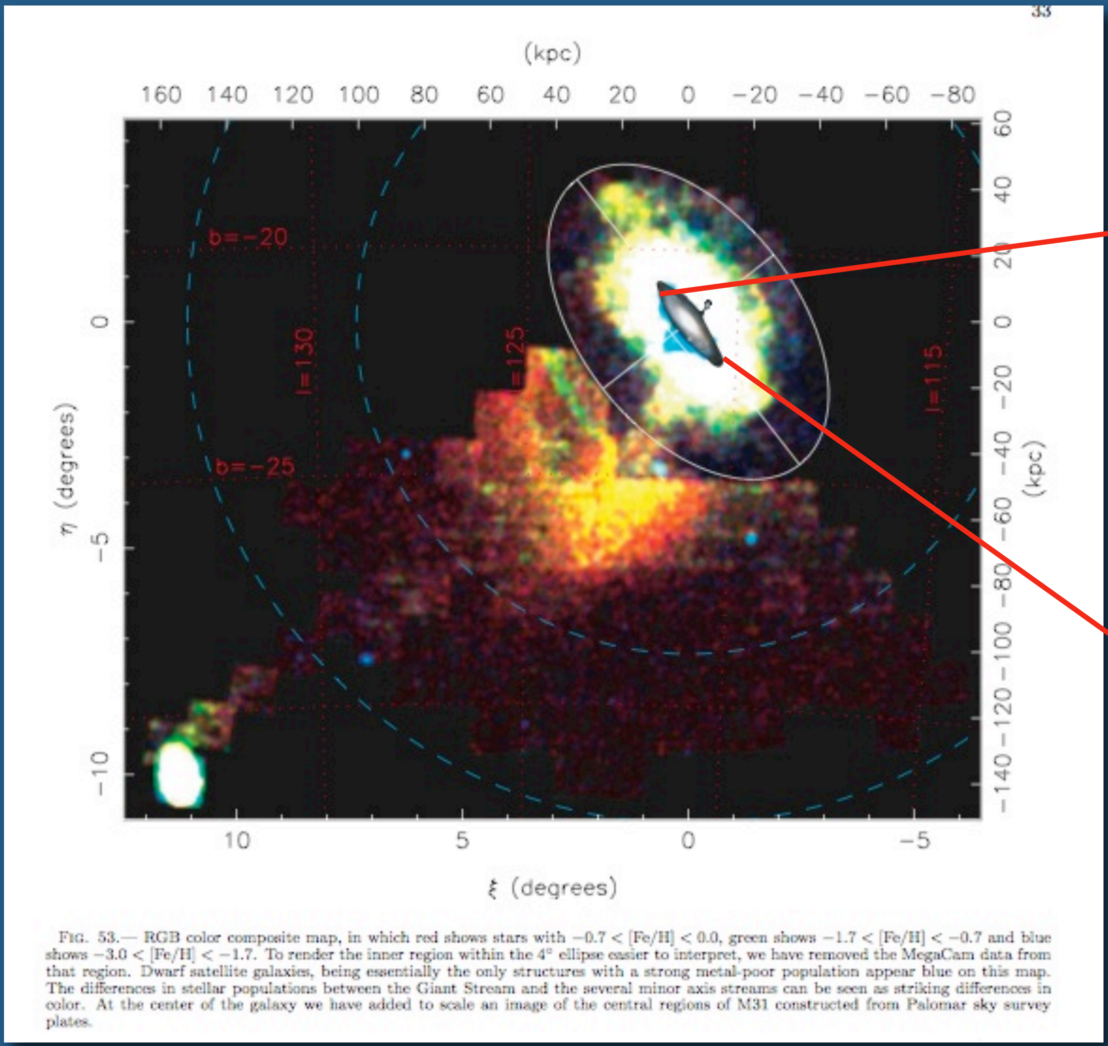
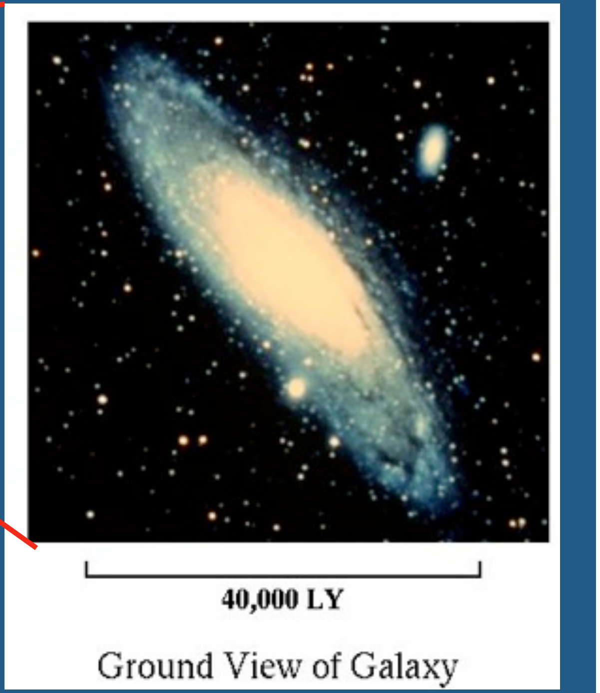
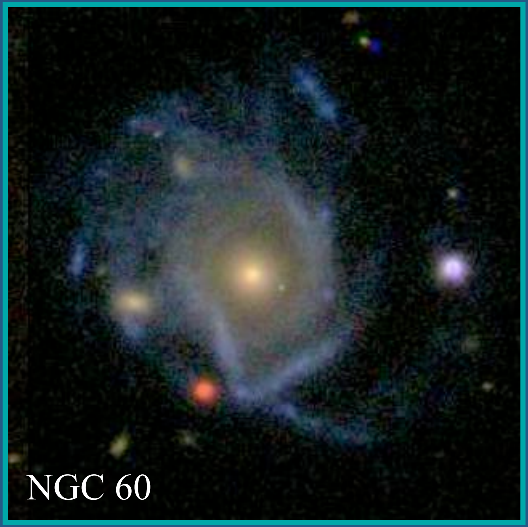


FIG. 53.— RGB color composite map, in which red shows stars with $-0.7 < [\mathrm{Fe/H}] < 0.0$, green shows $-1.7 < [\mathrm{Fe/H}] < -0.7$ and blue shows $-3.0 < [\mathrm{Fe/H}] < -1.7$. To render the inner region within the 4° ellipse easier to interpret, we have removed the MegaCam data from that region. Dwarf satellite galaxies, being essentially the only structures with a strong metal-poor population appear blue on this map. The differences in stellar populations between the Giant Stream and the several minor axis streams can be seen as striking differences in color. At the center of the galaxy we have added to scale an image of the central regions of M31 constructed from Palomar sky survey plates.



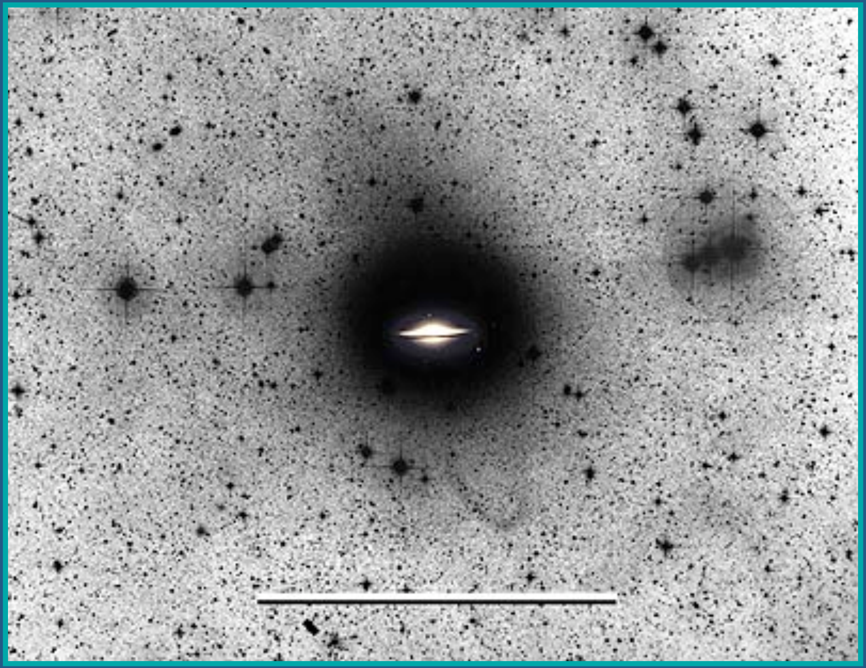
Ground View of Galaxy

Perturbed Spiral Galaxies, Tidal Streams


NGC 60


NGC 5719

SDSS

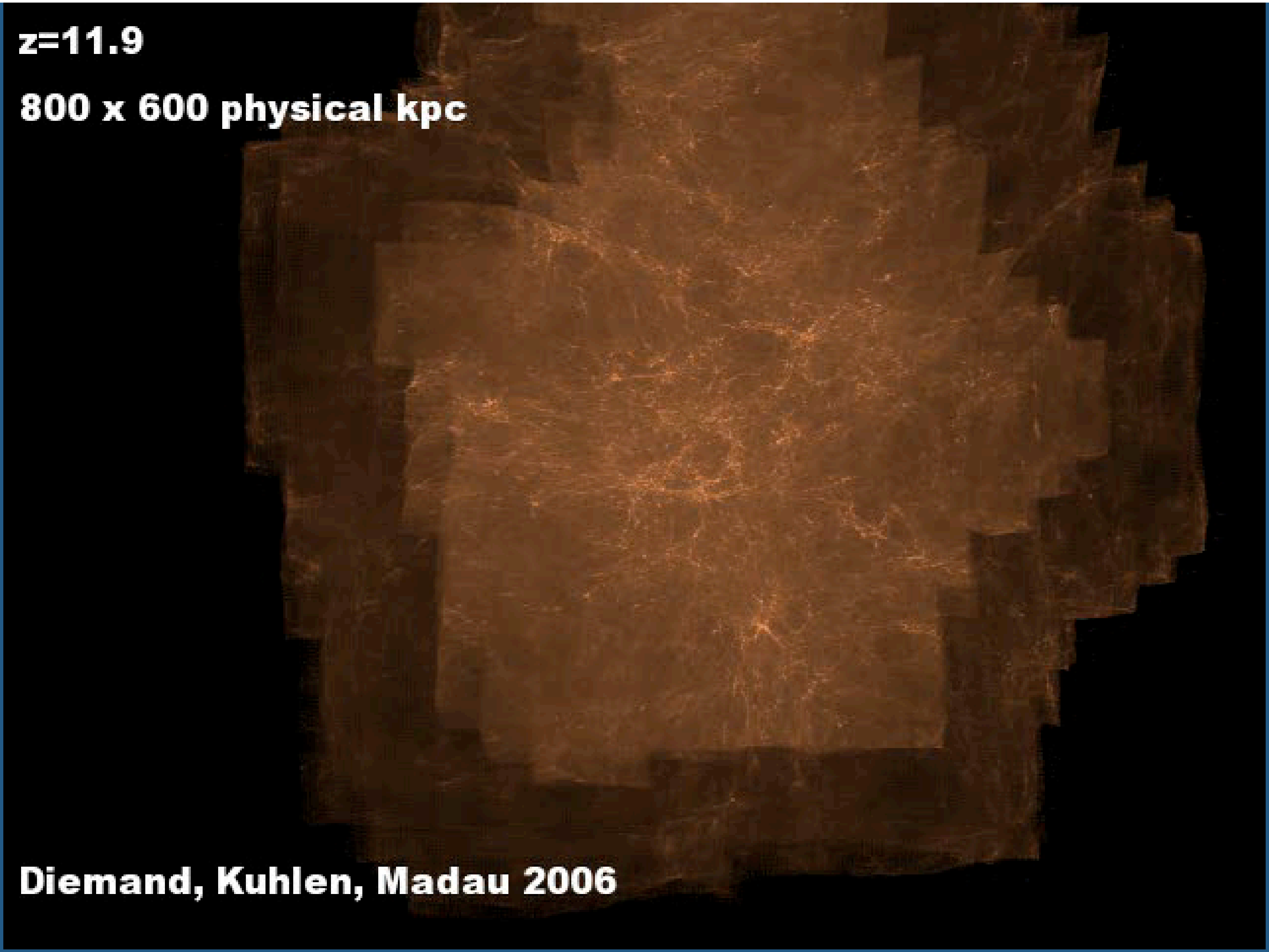

M 104 D. Malin -AAT

HOW DID IT ALL FORM?

COSMOLOGY:

Galaxies formed via hierarchical merging, where the merging elements were a mixture of baryonic and dark matter (DM). DM settled into a partly virialized spherical halo while baryons (in disk) galaxies settled into a rotating disk and bulge; the luminous halo formed via accretion of satellites (including globular clusters).

The ΛCDM cosmology has been confirmed by the cosmic background anisotropy measurements (WMAP results, Spergel et al. 2003), and other cosmological probes; it is remarkably successful at reproducing the large scale observations (cluster of galaxies, formation of elliptical galaxies via hierarchical merging).



Laregest resolution N-body experiment to date (234 million particles on ~ 320,000 CPU hours simulation
on NASA's Project Columbia supercomputer)

Disk galaxies (and their satellite systems) present a challenge to hierarchical formation models in the currently widely accepted ΛCDM cosmology.

Problems with disk galaxies:

-cuspy cores predicted by theory are not supported by the observations of rotation curves in disk galaxies (except for low surface brightness galaxies); inner regions and the disk of our Galaxy is gravitationally dominated by the luminous matter.

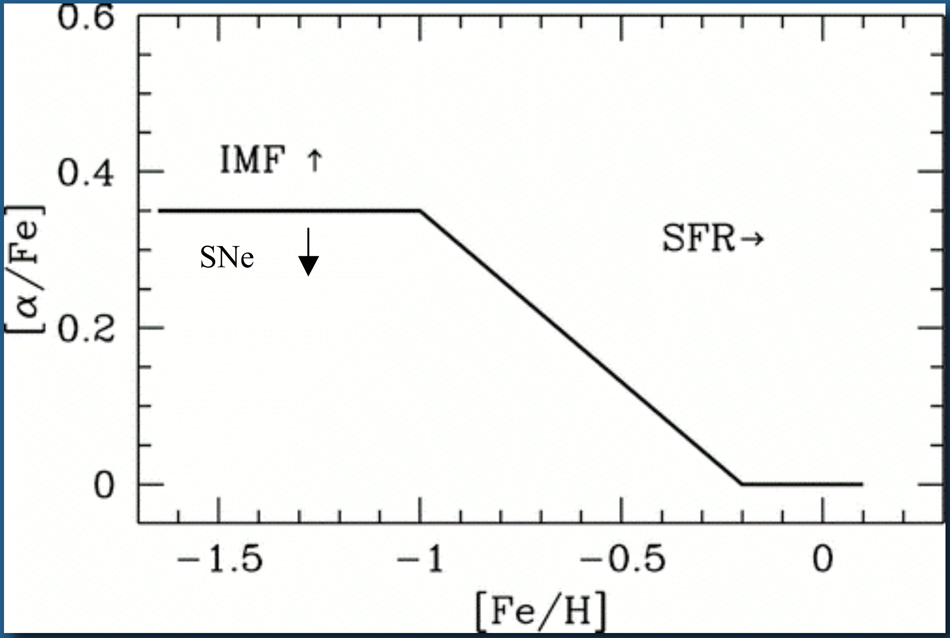
-still the highest resolution models (Diemand et al. 2007) available to date predict a large amount of substructure (~10000 subhaloes for a MW-size galaxy), compared to visible MW satellites (including the most recent SDSS findings, in all some 20 satellites). However, most of the subhaloes are now believed to be DM-only . Solution a) Only 10% of the subhaloes were able to form stars and become galaxies (masses ~> 10**9 M_sun at high redshift, or the largest before accretion onto the host halo, Kravtsov et al. 2004), and/or b) forming in rare density peaks selected at z > 12 (earliest formed to avoid SF suppression from the UV background radiation; Moore et al. 2006).

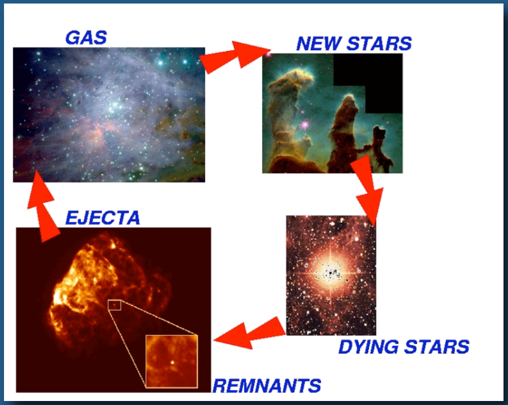
-initial N-body models predicted too small (mass and size) disks; newer models (Governato et al. 2007, N-body+SPH), obtain more realistic disks by using high resolution N-body codes, and feedback from SNe and SF. Also, UV background radiation and SNe feedback reduce the number of visible satellites.

HOW DID IT ALL FORM?

CHEMISTRY:

-If the halo has formed via merging from some “building blocks”, the chemical abundance patterns seen in the “building blocks” and in the stars in the halo should match. Assume the “building blocks” are the dwarf satellites of the MW.

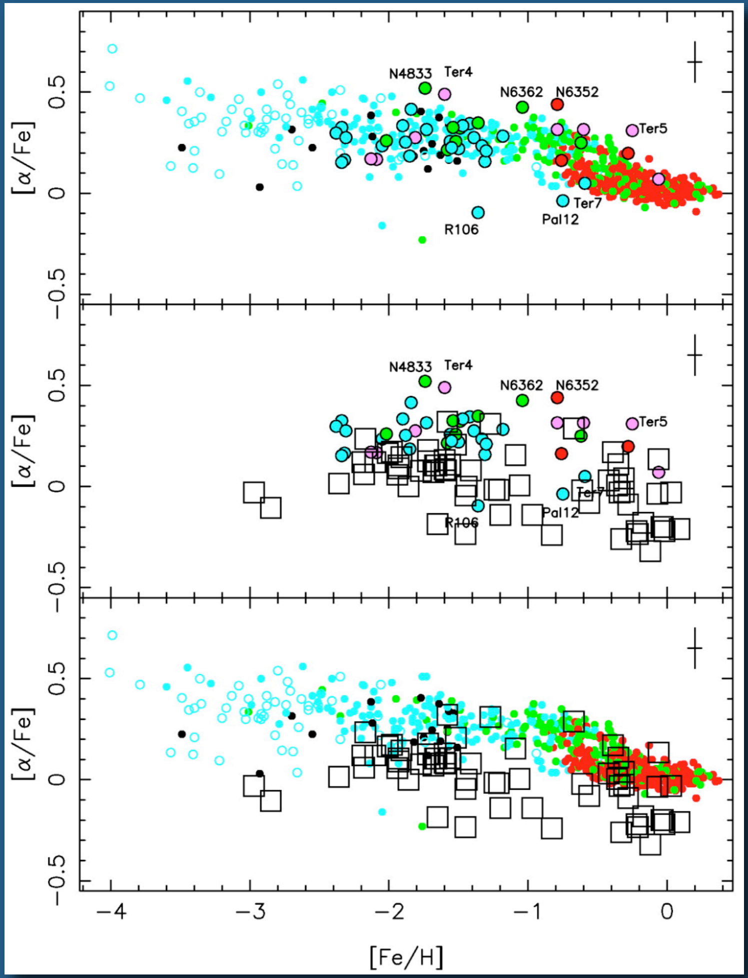




www.astro.uiuc.edu/classes/ (lecture notes)

McWilliam 1997: A schematic diagram of the trend of alpha-element abundance with metallicity. The knee in the diagram is thought to be due to the onset of type Ia supernovae

CHEMISTRY (cont.)



The chemical abundance profiles of MW satellites indicate that they were not the “building blocks” of the inner halo.

Pritzl et al. 2005

CHEMISTRY (cont.)

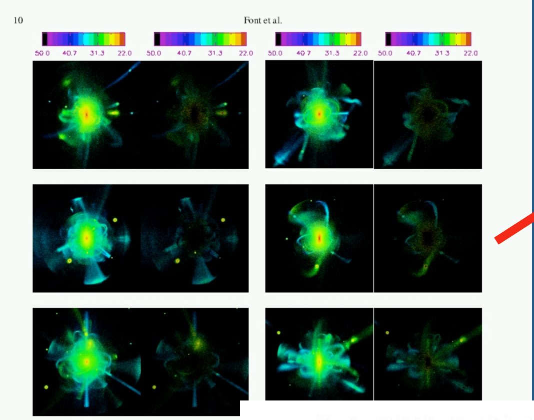
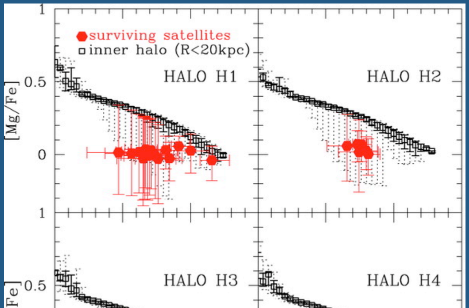

10 Font et al.

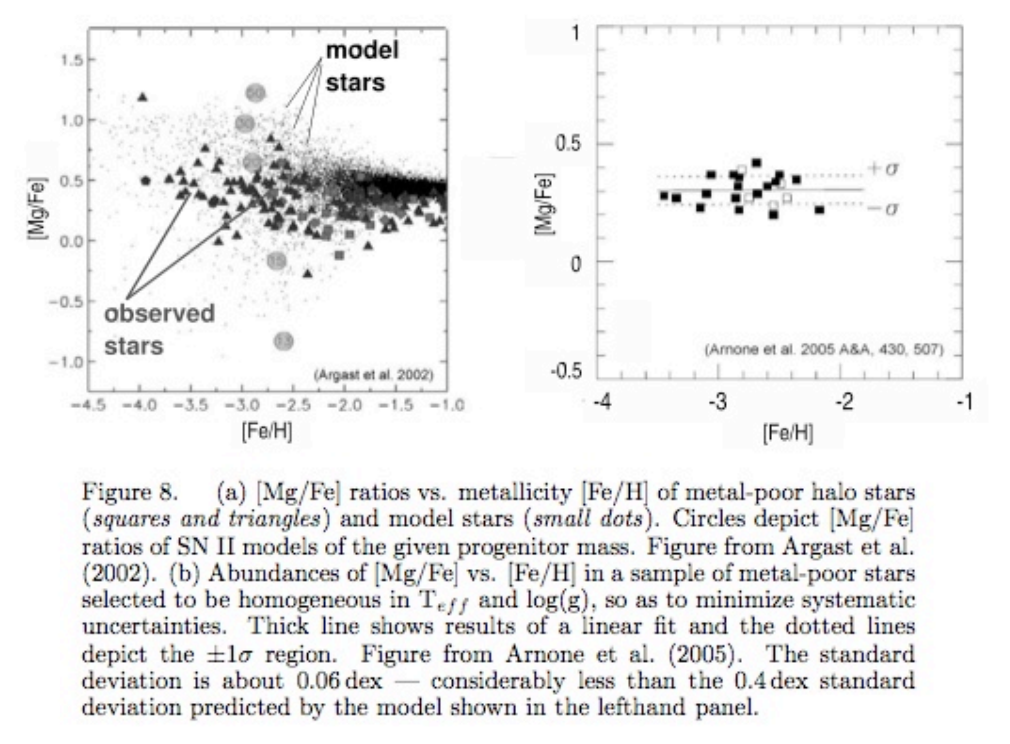
FIG. 11.— V-band surface brightness maps for halos H1, H2, H3, H4, H

brightness map of all stars and right sub-panels the corresponding surface

Low α

Font et al. 2006





(Argast et al. 2002)

(Arnone et al. 2005 A&A, 430, 507)

Figure 8. (a) [Mg/Fe] ratios vs. metallicity [Fe/H] of metal-poor halo stars (*squares and triangles*) and model stars (*small dots*). Circles depict [Mg/Fe] ratios of SN II models of the given progenitor mass. Figure from Argast et al. (2002). (b) Abundances of [Mg/Fe] vs. [Fe/H] in a sample of metal-poor stars selected to be homogeneous in T_{eff} and log(g), so as to minimize systematic uncertainties. Thick line shows results of a linear fit and the dotted lines depict the ±1σ region. Figure from Arnone et al. (2005). The standard deviation is about 0.06 dex — considerably less than the 0.4 dex standard deviation predicted by the model shown in the lefthand panel.

From a realistic co

I+Type II) and Mg

ones, and they are

galaxies accreted

should be dominat

long and slow SF

tion - for Fe (Type

that of the merged

ilt from satellite

II). The outer halo

r on, and that had a

However this is not a

1) Other abundance patt

dels…)

2) The scatter in other e

l picture (remarkably low

scatter! Cayarel et al.

3) Globular clusters at l

r halo

HOW DID IT ALL FORM?

KINEMATICS (radial velocities and proper motions):

1) Use Galactic satellites, tidal streams, globular clusters as “test particles” to probe the Galactic potential and model the Galactic interactions. Therefore, constraints are provided for the orbit shapes and masses of progenitors, and the shape of the DM halo.

2) Characterize the main Galactic components – disk, thick disk, halo, bulge/bar. I.e., measure their mean velocities, velocity dispersions and the corresponding gradients over the relevant size of each component.

Proper Motions, Velocities and Uncertainties

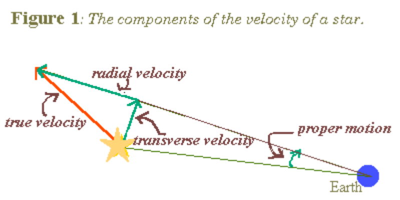


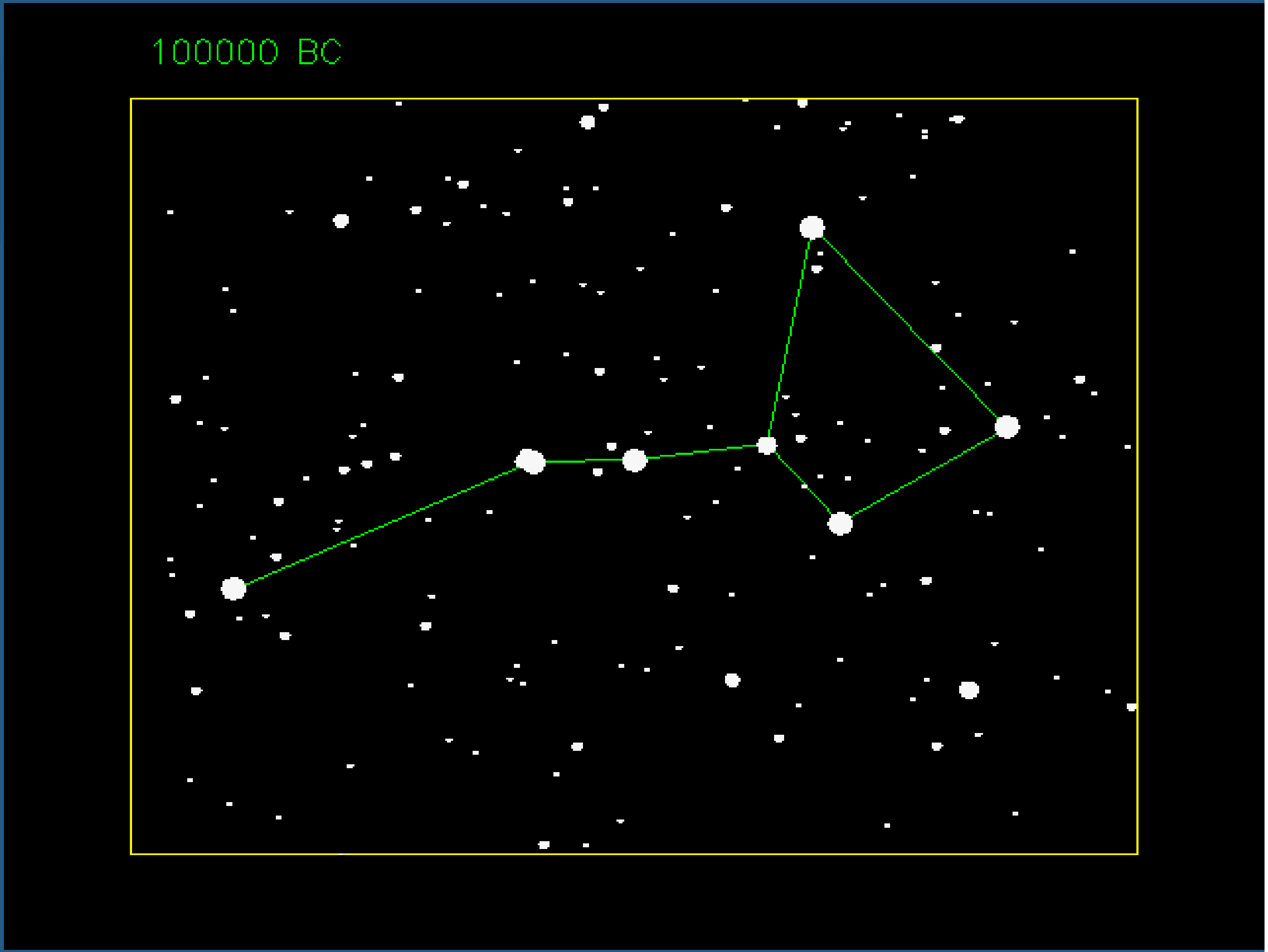
Figure 1: *The components of the velocity of a star.*

Proper motions contain information on two velocity components of the target; to extract this information one needs to have:

- absolute proper motions, i.e., with respect to an inertial reference frame.

- distance to the targets

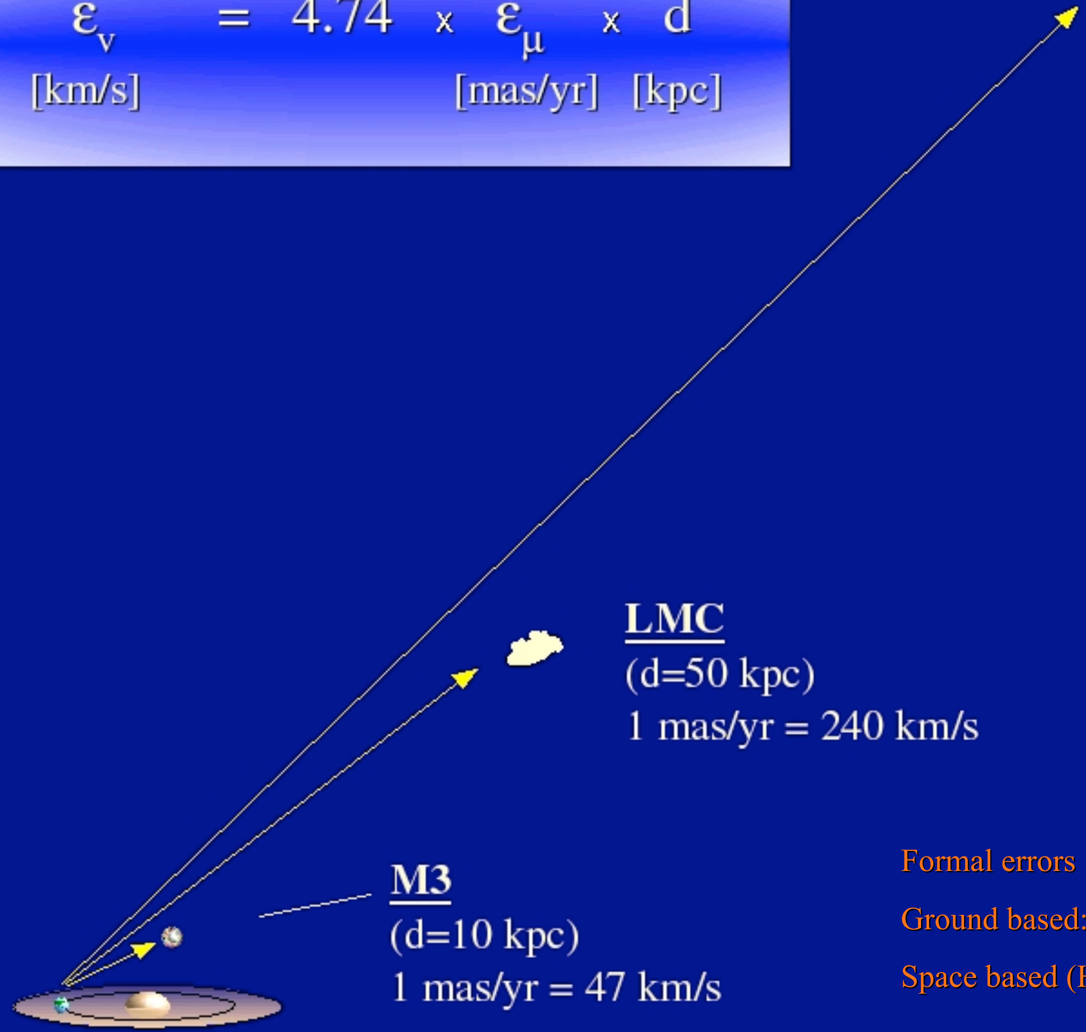
- the Solar motion



Big Dipper: from 100,000 BC to 100,000 AD; Richard Pogge – Ohio State U., Astronomy Dept.

Proper Motions, Velocities and Uncertainties (cont.)

$$\underset{[\mathrm{km/s}]}{\varepsilon_v} = 4.74 \times \underset{[\mathrm{mas/yr}]}{\varepsilon_\mu} \times \underset{[\mathrm{kpc}]}{d}$$



Fornax dSph
(d=138 kpc)
1 mas/yr = 650 km/s

LMC
(d=50 kpc)
1 mas/yr = 240 km/s

M3
(d=10 kpc)
1 mas/yr = 47 km/s

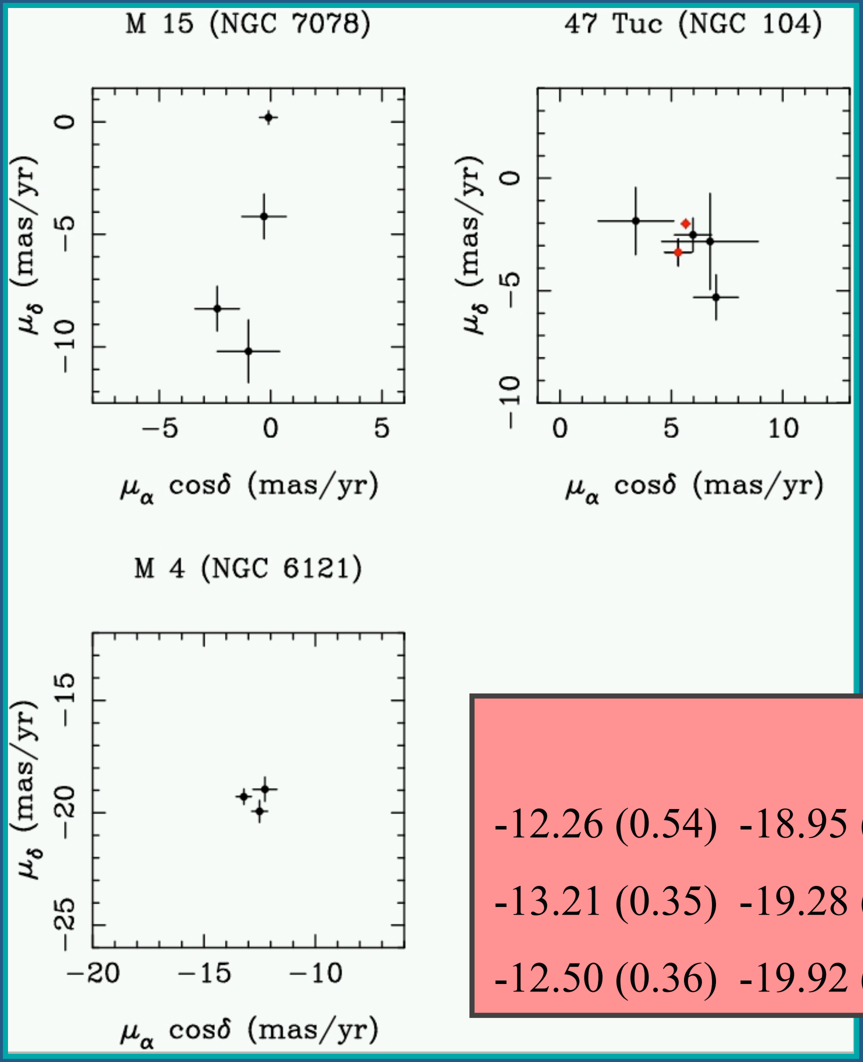
Milky Way

Formal errors

Ground based: between 0.1 and 0.5 mas/yr

Space based (HST): between 0.05 and 0.20 mas/yr

Measurements of Absolute Proper Motions: Globular Clusters

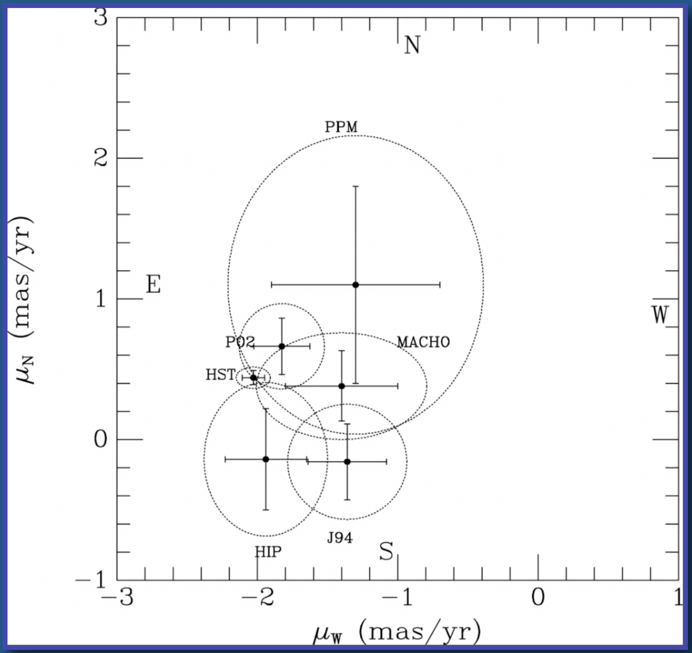


M 4

-12.26 (0.54)	-18.95 (0.54)	Kalirai et al. 2004 – HST, ~12 galaxies
-13.21 (0.35)	-19.28 (0.35)	Bedin et al. 2003 – HST, 1 QSO
-12.50 (0.36)	-19.92 (0.49)	Dinescu et al. 1999 - SPM, ~100 Hipparcos stars

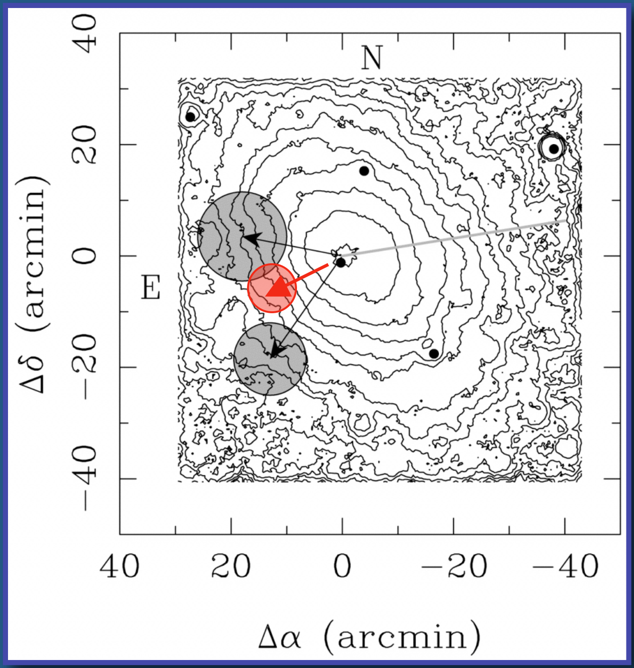
Measurements of Absolute Proper Motions: Satellite Galaxies, Tidal Streams, Overdensities

LMC – 50 kpc



Kallivayalil et al. 2006

Fornax dSph – 140 kpc



Piatek et al. 2002, Dinescu et al. 2004, see also Piatek et al. 2006 which agrees with Dinescu et al. 1999

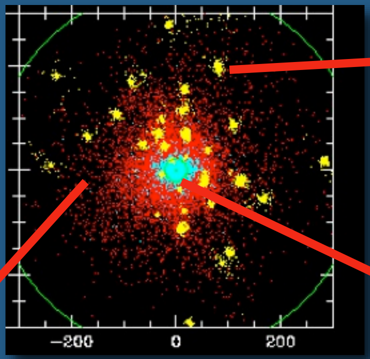
For distant satellites: poor proper motions (poor agreement when there are multiple measurements). Can not constrain well orbit shapes!

KINEMATICS: predictions/observations for accreted and surviving satellites

-few predictions, mainly available for satellites

-lack of detailed predictions for 3D velocities (means, dispersions) and their spatial gradients for the smooth galactic components: thick disk, halo

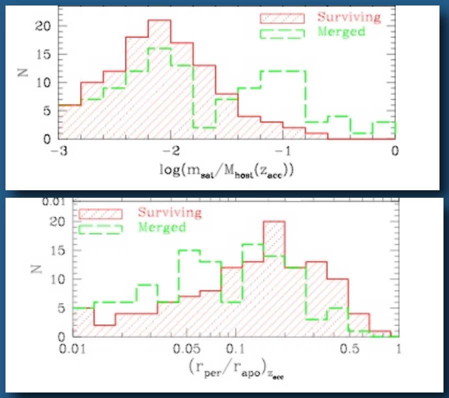
Sales et al. 2007: stellar component



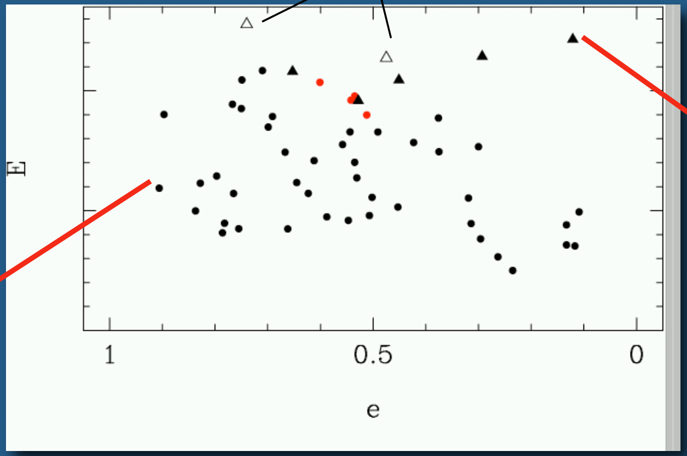
surviving satellites

accreted satellites

“in situ”, host halo



LMC: 2 measurements!



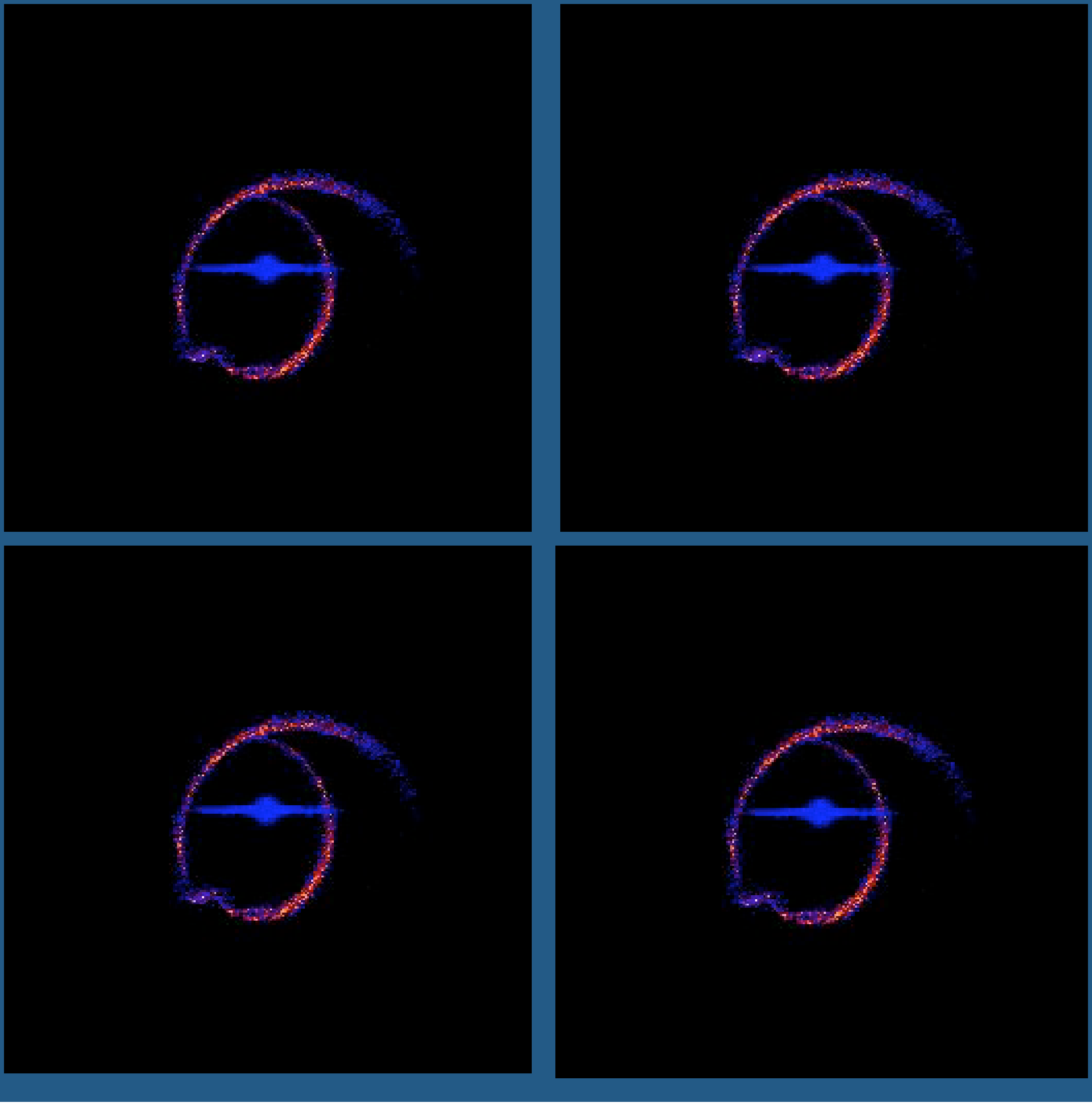
Observations: Casetti-Dinescu et al 2007, 2004, 1999, Piatek et al. 2003,2005,2006 and other compilations

GCs

dSph

KINEMATICS: Tidal streams

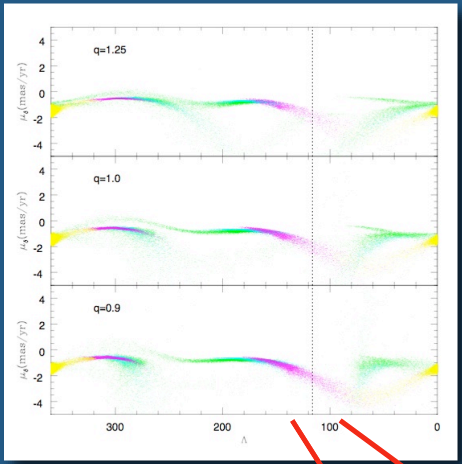
Tidal stream mapping and 3d kinematics can constrain the shape and the lumpiness of the host halo DM potential, and the initial mass of the satellite.

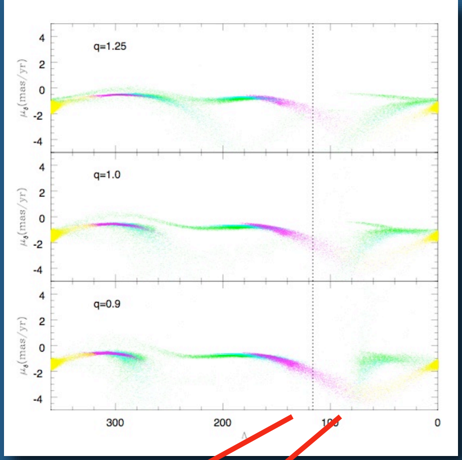


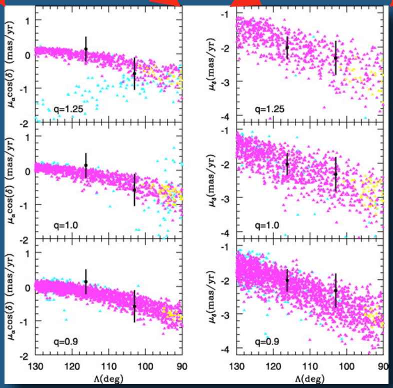
Sagittarius models:
Johnston, K. 2007,
Law et al. 2005

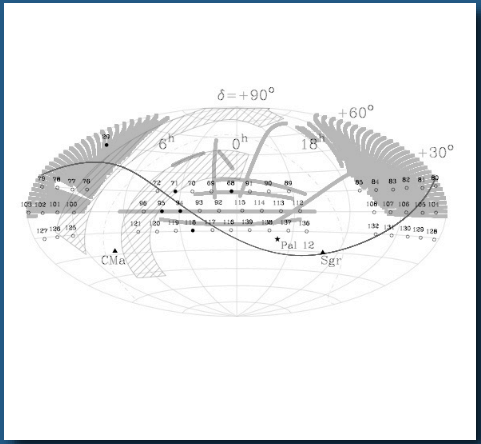
KINEMATICS: Tidal streams (cont.)

Sagittarius dwarf: proper motions along the trailing tail





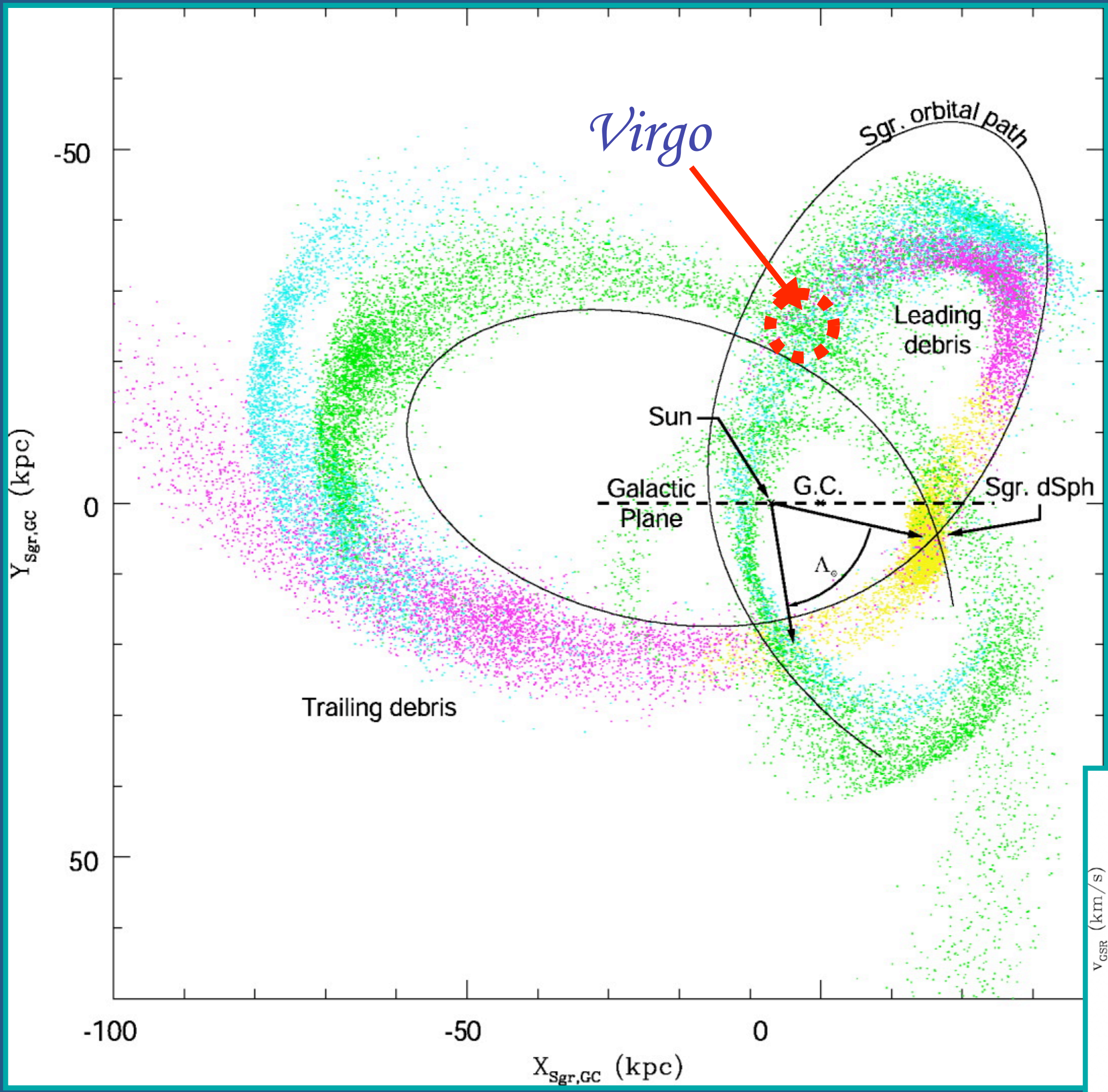


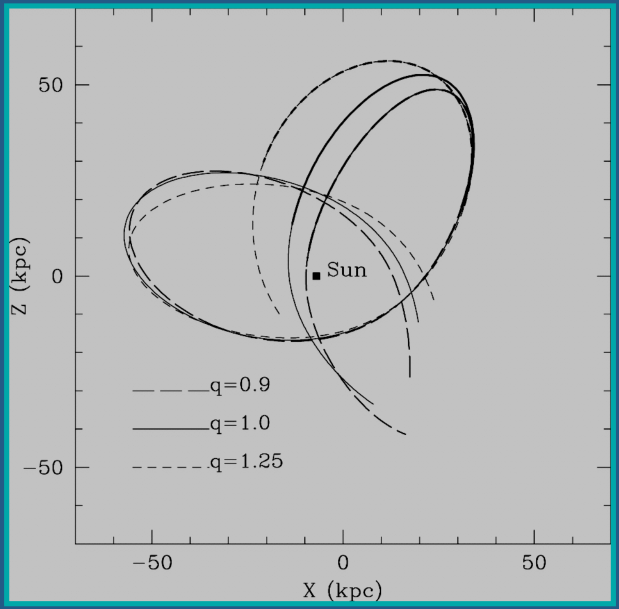


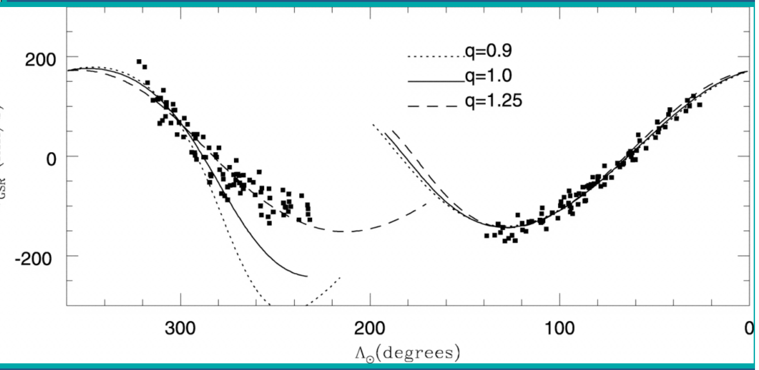
Casetti-Dinescu et al. 2006, Law et al. 2005

KINEMATICS: Tidal streams (cont.)

Martinez-Delgado: the Virgo structure is another tidal stream of Sagittarius (for appropriate dark halo potential - oblate)

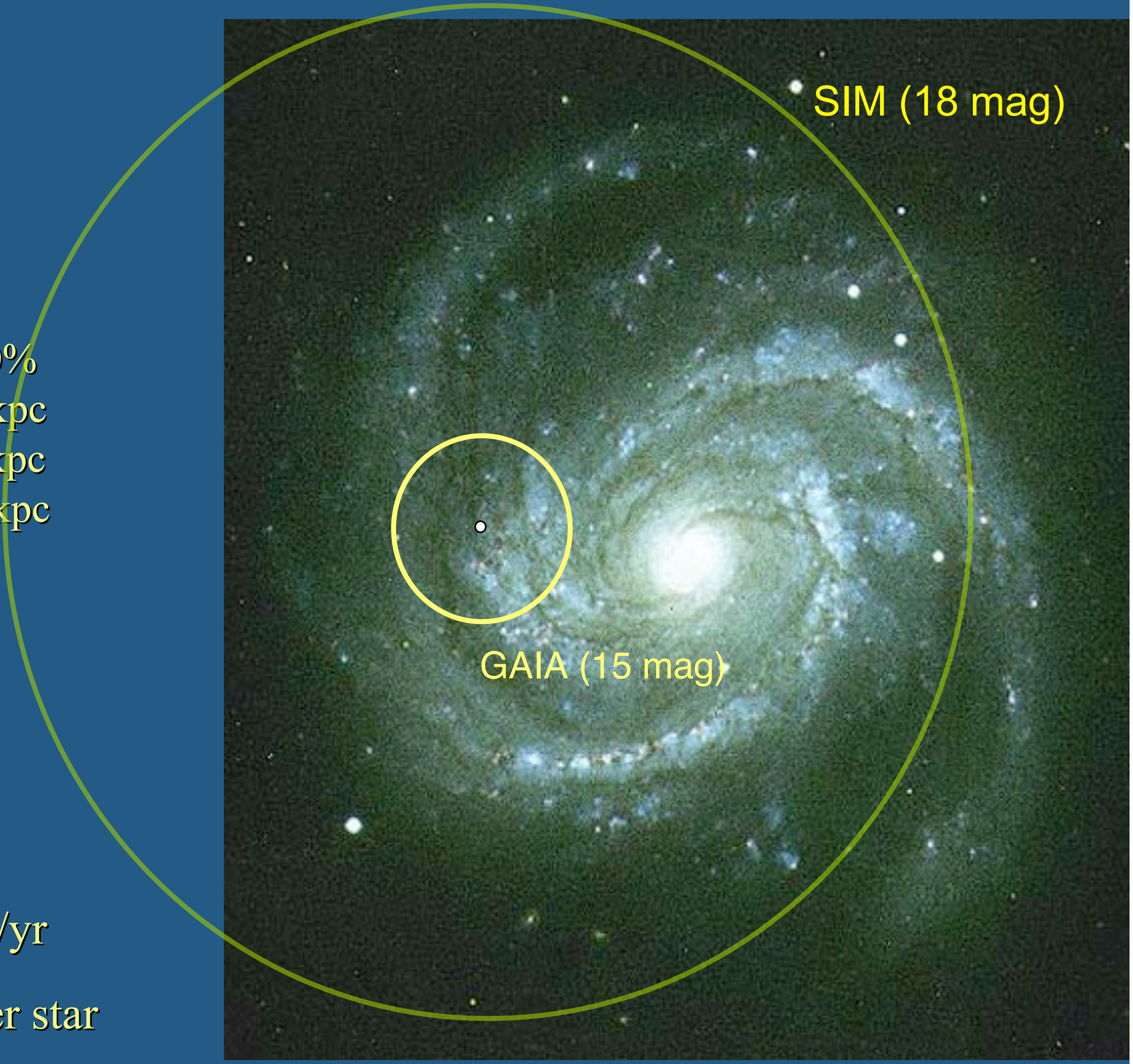






Helmi 2004: prolate halo from RVs; Law et al. 2005: oblate from the precession of the orbit

KINEMATICS: The Future



Distances

	1%	10%
SIM	2.5 kpc	25 kpc
GAIA	0.4 kpc	4 kpc
Hipparcos	0.01 kpc	0.1 kpc

Proper Motions:

SIM ~ few μas/yr

GAIA ~ few tens of μas/yr

Hipparcos ~ 1 mas/yr per star

SUMMARY

-The MW stellar halo, as well as the other components (disk, thick disk, halo, bulge) are complex structures that can place strong constraints on the formation picture of a disk galaxy in the context of cosmology.

-To understand the details of the picture, kinematical and spectroscopic surveys play a key role; this can be done only in the Local Group.